DESCRIPTION

Title of the invention: Microwave signal amplifier with isolation

Technical field – technological background

[0001] The invention relates to the field of amplifiers for very weak electromagnetic signals, especially but not only for quantum computing.

[0002] In particular, the invention relates to the field of circuits for transmitting microwaves. It is a question of designing and managing these circuits in such a way as to ensure that the signals of interest are amplified, that no parasitic signals are generated, and that ambient noise and the noise of the components used is kept away from the amplification chain or filtered in it, in the direction of amplification but also in the opposite direction, because it is necessary to avoid exposing the signal source to waves that would otherwise reach it through the read chain – which would then be passed through in the reverse direction – and would thus disrupt it. When it is a question of avoiding the transfer of waves in the reverse direction, the problem is said to be one of obtaining isolation of the source, and this is a task in itself.

[0003] The circuits in question may be highly integrated circuits. They are based on components with superconducting properties, i.e. so-called superconducting components, that are placed in cryogenic enclosures in order to benefit from a temperature of at most a few K (a few kelvin).

[0004] Typically, the superconducting circuit in question is an amplifying circuit intended to amplify a microwave issuing from a qubit or quantum bit, the state of which it is desired to know. It may alternatively be intended to read information regarding spin magnetic resonance (in other words electron paramagnetic resonance) or even to amplify a radio wave of astronomical origin. In all these situations, a microwave of very low power is to be amplified.

[0005] In this context, parametric amplifiers based on a medium exhibiting a nonlinear behavior are known, these allowing wave mixing, i.e. in particular the transfer of energy from one frequency to another. The nonlinear behavior is

modified through regulation of the medium, to obtain the phase matching required for the wave mixing.

[0006] In a parametric amplifier performing four-wave mixing (via the Kerr effect), two waves are incident: the pump wave of angular frequency ωp and the wave to be amplified or signal wave of angular frequency ωs. The amplifier transfers energy from the pump wave to the signal wave, which is therefore amplified, and also creates an idler wave at an angular frequency ωc in order to keep total energy unchanged.

[0007] Superconducting elements such as Josephson junctions form the hardware medium in which the nonlinearity on which the parametric amplification of the waves that are made to pass therethrough is based is observed. Hence the term Josephson parametric amplifier (JPA) is employed. Josephson parametric amplifiers are efficient in the microwave domain.

[0008] To obtain significant gains, standing-wave amplifiers built around a resonant cavity have been proposed, as in Planat, 2018, Phys. Rev. Applied 11, 034014 – 2019. The bandwidth is of the order of 45 MHz. It may be multiplied by 10 by performing impedance matching.

[0009] Traveling-wave parametric amplifiers (TWPAs) have also been proposed, for example in US8878626B2. In these structures, many nonlinear elements connected in a chain form a transmission line for signal propagation. Phase matching may be achieved through the presence of resonators on the line, as in Macklin, Science, 2015, 350, 6258, 307 or modulation of the dimension of the line, as in US8878626B2.

[0010] In US2018/0034425A1, the chained elements are assemblies of Josephson junctions connected to form loops. The loops are coupled asymmetrically, and each by four poles. Regulation is achieved by adjusting the magnitude of a magnetic flux that is arranged to pass through the loops.

[0011] Amplification in the TWPAs is obtained by virtue of a wave-mixing process resulting from coupling between propagation modes in the nonlinear medium: the medium is excited with a strong pump wave, at the frequency ωp, causing

amplification of a weaker signal, at the frequency ωs, and creation of an idler wave, at the frequency ωc. The bandwidth of a TWPA may be a few GHz. In practice, distortion is generated in the dispersion relationship by opening a photonic space in the dispersion relationship by periodically modulating the transmission line or by creating a stop band by introducing resonant elements into the transmission line. Nevertheless, significant ripples are observed in the gain profile. Furthermore, the band of amplification is set by design.

[0012] Known traveling-wave parametric amplifiers or TWPAs let the signal pass from the input of the amplifier to the output of the amplifier, but also let existing noise pass from the output to the input. They are therefore said to be reciprocal.

[0013] Such reciprocal traveling-wave parametric amplifiers must, because of their reciprocal nature, be used in conjunction with an additional microwave component called an isolator, which allows the isolation mentioned in the introduction to be obtained. This component, which is placed between the low-power microwave source that it is desired to amplify and the traveling-wave amplifier (and therefore in general in a very low-temperature enclosure), makes it possible to filter, in the direction running from the read devices to the source, parasitic signals generated by the traveling-wave amplifier itself or by the components or environment existing on the other side of the amplifier, for example such as an additional amplifier in HEMT technology (HEMT standing for High Electron Mobility Transistor). However, these microwave isolators have a large physical footprint (and use magnetic fields: they are components comprising permanent magnets, the magnetic fields of which may affect the qubits and superconducting amplifiers) and cannot be integrated directly into a chip. It is therefore not easy or very economical to place such an amplifier in a very low-temperature enclosure, in which it is desired to multiplex many signals. Alternatively or in conjunction with isolators, circulators could be used, but these components also have a large footprint.

[0014] Lecoq et al., Phys. Rev. Applied 7, 024028 2017 and Lecoq et al., Phys. Rev Lett. 126, 020502, 2020 mention use of a Josephson parametric amplifier with a loop in frequency space. These authors argue that this amplifier protects the read cavity and the qubit on which they implement it. The system is a standing

wave system requiring four microwave sources, and its bandwidth – of about 10 MHz – is narrow.

[0015] Ranzani et al., Phys Rev. Applied 8, 054035, 2017, presented a transmission line based on Josephson junctions, in groups of five with a total of 740 junctions, inserted between segments of 50 Ω transmission line. A pump tone (or wave) at ωp modulates the line inductance, allowing for frequency conversion of a signal copropagating with the pump.

[0016] Frattini et al., Appl. Phys. Lett. 110, 222603, 2017, presented a dipolar element called the SNAIL (for Superconducting Nonlinear Asymmetric Inductive eLement) consisting of four Josephson junctions split between two arms, three large junctions (tunnel energy Ej) in one arm and one small junction (tunnel energy αEj) in the other arm. This element makes it possible to achieve three-wave mixing. Subsequently, Frattini et al., Phys. Rev. Applied 10, 054020, 2018 disclosed a chain of 20 SNAIL dipolar elements (consisting of 3 large junctions Lj and one small junction Lj/α) in series, all the elements being subjected to an identical magnetic flux varying from 0 to 0.5 flux quanta. The authors discuss optimization of amplification by three-wave mixing, and minimization of four-wave mixing.

[0017] Perelshtein et al., 2022, Physical Review Applied 18, 024063 uses SNAILs (1632 in number) comprising only three Josephson junctions: one small junction, αEJ, in one arm and two large junctions, EJ, in the other arm, the dipolar orientation remaining the same throughout the chain. For a flux quantum of zero, the line impedance is less than 50 Ω and there is no 3-wave mixing. At a flux quantum of 0.4, these authors observed 3-wave mixing, and a little 4-wave mixing.

[0018] Ranadive et al., Nature Communications, 2022, 13, 1737 suggested alternately reversing the orientation of SNAILs with respect to the external field, to suppress three-wave mixing processes (the SNAILs are placed with alternating magnetic flux polarity, i.e. they are physically oriented in a way such that magnetic flux biasing is reversed for adjacent SNAIL cells, taking advantage of the fact that this means that the coefficient g3 of 2nd order nonlinearity quantifying three-wave mixing is an odd function of the external flux). The system comprises, at 20 mK,

700 cells spanning 6 mm, with each cell containing a superconducting loop with three large (critical current I0) and one small (low critical current, rI0) Josephson junctions in either arm. The ratio of the critical current of the small and large Josephson junctions (r) is chosen such that the magnitudes of the second-order nonlinearity (g3) and third-order nonlinearity (g4) are anti-correlated. These authors observed a significant amplification for a flux quantum of 0.5, with reference to the unity magnetic flux quantum Φ0. These authors thus present a broadband transmission line with a strong third-order nonlinearity – which therefore allows four-wave mixing – the coefficient g4 of which may be adjusted to positive or negative values. The reported effect is called reversed Kerr phase-matching. The combined bandwidth is declared as 3 GHz, with no gaps in transmission.

Summary of the invention

[0019] In addition to being reciprocal, TWPAs suffer from reflections at their junction with transmission lines, and from backward emission.

[0020] The present invention solves the problem of isolation, because the proposed principles break the reciprocity of existing amplifiers and therefore do not allow signals or noise to propagate from the output of the amplifier to its input and therefore to the device under test.

[0021] To do this, provision is made for a microwave signal amplifier comprising a chain of nonlinear inductive dipolar elements each forming one superconducting asymmetric loop of Josephson junctions, said chain being arranged between an input of the chain where a signal to be amplified of known frequency is applied and an output of the chain where an output signal develops, the amplifier in addition comprising a controllable system for generating magnetic flux with a view to making a current flow through said loops, the amplifier in addition comprising a first microwave pump and a means for coupling said input of the chain to the first pump, the first pump generating through the first coupling means a wave in the chain in the direction running from the input to the output of frequency set to transfer power to microwaves propagating in a band around the frequency of the signal to be amplified.

[0022] The amplifier further comprises a second microwave pump and a second coupling means for coupling said output of the chain to said second pump, the second pump generating through the second coupling means a wave in the chain in the direction running from the output to the input, at a frequency different from the frequency of the first pump and so as to attenuate in said direction running from the output to the input microwaves propagating in a band (in general different from the preceding band mentioned with regard to amplification) around the frequency of the signal to be amplified. This attenuation may be achieved via a frequency-conversion mechanism.

[0023] The principles thus described make it possible to obtain a traveling-wave parametric amplifier which is also a powerful isolator in the reverse direction, over a bandwidth of several hundred MHz (typically 800 MHz) and which may be adjusted over several GHz, with a central frequency of 6 GHz typically. With such a device, additional bulky magnetic microwave isolators, or circulators, are avoided: it is possible to achieve a connection without an intermediate isolator between the microwave source to be amplified and the parametric amplifier. The footprint of the elements to be installed in the cryogenic enclosure is therefore limited. The amplification may be achieved with a gain of 20 dB while obtaining isolation of 30 dB in the other direction.

[0024] Noteworthily, these principles require only two microwave pumps, and not three or four like certain devices of the prior art. This is noteworthy from the perspective of scaling up.

[0025] With these principles, in addition, the gain profile is regular, without abrupt ripples as in devices in which phase matching is obtained by modulation of the width of a line based on single Josephson junctions, which have impedance mismatches.

[0026] According to advantageous and optional features:

- the dipolar elements of the chain may be identical, and the magnetic flux is, divided by the flux quantum of the loops, set so as to be non-zero modulo 0.5, and

preferably so as to be between 0.05 and 0.35, and preferably between 0.1 and 0.3;

- nonlinear asymmetric inductive elements of the chain may comprise, between their two poles, a first arm and a second arm that are connected in parallel with each other, the first arm consisting of an array of at least two Josephson junctions in series, the second arm consisting of a single Josephson junction or of a second array of Josephson junctions in series, a number of Josephson junctions in the second array being lower than a number of Josephson junctions in the first array;

- the dipolar elements and the system for generating magnetic flux may be configured in such a way that the asymmetric loops of successive dipolar elements along the chain are subjected to a magnetic flux of similar magnitude but the direction of which is opposite from one asymmetric loop to a following loop in the chain, and preferably from one asymmetric loop to the immediately following loop in the chain;

- the nonlinear asymmetric inductive elements may comprise, between their two poles, an arm comprising one or more identical small Josephson junctions and an arm comprising one or more identical large Josephson junctions, a ratio r of the critical current of small and large junction being between 0.01 and 0.25, and preferably between 0.05 and 0.20;

- the superconducting nonlinear asymmetric inductive elements may comprise, between their two poles, an arm comprising a single so-called small Josephson junction and an arm comprising three identical so-called large Josephson junctions in series;

- the nonlinear asymmetric inductive elements may comprise small and large Josephson junctions, the small Josephson junctions having an inductance between 1300 and 2500 pH and preferably between 1600 and 2200 pH, or the large Josephson junctions having an inductance between 100 and 300 pH and preferably between 140 and 260 pH;

- the system for generating magnetic flux may consist of a single electromagnet developing a uniform magnetic field over the entire chain;

- the chain may comprise between 500 and 1300 nonlinear inductive dipolar elements, and preferably between 600 and 850;

- the first pump may emit a microwave at a frequency between 5.2 and 10.5 GHz, and preferably between 6.0 and 10 GHz;

- the second pump may emit a microwave at a frequency between 8.4 and 13.5 GHz, and preferably between 9.7 and 13.5 GHz;

- a frequency difference between the microwaves emitted by the first pump and the second pump may be between 2 and 6 GHz, the second pump emitting at a higher or lower frequency than the first pump;

- the signal to be amplified may be present at a frequency of the order of between 5.0 and 7.8 GHz, and preferably between 6.0 and 6.4 GHz. Typically, it is a question of a signal issuing from a qubit;

- the first coupling means may be a diplexer applying a high-pass filter to the microwaves of the first pump and directing them to the chain, and applying a low-pass filter to the microwaves of the signal to be amplified and also directing them to the chain;

- the second coupling means may be a diplexer applying a high-pass filter to the microwaves of the second pump and directing them to the chain, and applying a low-pass filter to the microwaves issuing from the chain and directing them to a read chain.

List of the figures

[0027] Figures 1 and 2 show a circuit according to one embodiment of the invention.

[0028] Figure 3 is a graph of numerical values of the obtained attenuation.

[0029] Figure 4 is a view of the variation in gain values, as a function of flux and frequency.

[0030] Figure 5 is a view of numerical gain values in one direction and in the reverse direction.

Detailed description

[0031] [Fig. 1] As shown in figure 1, a chain of superconducting nonlinear asymmetrical inductive elements (SNAILs) is inserted at the center of a section of transmission line, indicated in the figure as being a 50 Ω transmission line – an impedance value used as standard – the transmission line for example being coaxial, and advantageously differential between two conductive lines.

[0032] The device consists of several hundred dipolar cells connected in series and spans in total a length of a few millimeters, each cell containing one superconducting loop with three large Josephson junctions (high critical current I0 or inductance L) and one small Josephson junction (low critical current rI0 with r<1 or inductance L/α with α<1) in one arm of the loop and in the other arm of the loop, respectively.

[0033] The chain of SNAILs – typically 700 SNAILs, but other values are possible – is fabricated on a silicon substrate using evaporation and deposition techniques. It connects a conductive line upstream of the chain to a conductive line downstream. The second conductive lines upstream and downstream are connected directly by a conductor. A dielectric layer, for example made of alumina, placed between the SNAIL chain and the copper line provides the ground capacitance required to match the impedance of the transmission line to a standard 50 Ω environment.

[0034] Within each SNAIL the junctions are all coplanar and the SNAILs of the chain are all coplanar. A current-carrying coil of a few centimeters in diameter is used to bias the device, with a low field asymmetry across the chain of SNAIL loops.

[0035] In one embodiment, the SNAILs are constructed with an alternation whereby, when considered in order from one end of the chain to the other end of the chain, for one SNAIL in two, the arm with the large Josephson junctions is on the left and the arm with the small Josephson junction is on the right, then for the following SNAIL, the arm with the large Josephson junctions is on the right and the arm with the small Josephson junction is on the left. This has already been discussed in Ranadive *et al.*, Nature Communications, 2022, 13, 1737. The

SNAILs are thus placed with alternating magnetic flux polarity, by being physically oriented in a way such that magnetic flux biasing is reversed for two adjacent SNAIL cells. In another embodiment, the alternation does not occur at every SNAIL, but every two SNAILs, or every N SNAILs, where N is an integer.

[0036] In the direction running from the left of the figure to the right, the following are introduced into the transmission line, which forms an amplification chain based on wave mixing: the signal to be amplified of angular frequency ωs (about 6 GHz, though that is not essential and other values are usable) which is of low amplitude, and a pump pulse which is of high but controlled amplitude, of angular frequency ωp quite close to ωs but for example greater than it.

[0037] Via a wave-mixing effect that is believed, without wishing nevertheless to be bound by this explanation, to be above all based on four-wave mixing – denoted 4WM in the figure – the signal of angular frequency ωs amplified by wave mixing develops at the end of the amplification chain, to the right of the figure. At this end is of course present the pump signal ωp, which has likewise traveled the chain. There is also at this end one or more idler waves, which have not been shown because they are not amplified.

[0038] In the direction running from the right of the figure to the left, the signal of angular frequency ωs having reached the end of the chain or beyond, and which was amplified, is reflected very partially in the transmission line due to any even modest change in impedance. Noise in the frequency range of the signal ωs may also be present and travel through the amplification line, from the output and in the direction of the source of the signal to be amplified.

[0039] A pump tone, of controlled amplitude, high in power, and of an angular frequency ωp' that, for example, is slightly further from ωs than ωp (therefore ωp' > ωp) is introduced into the chain through the output. ωp' depends on the process used to fabricate the Josephson junctions.

[0040] Via a wave-mixing effect that is believed, without wishing nevertheless to be bound by this explanation, to be above all based on three-wave mixing – denoted 3WM in the figure – the signal of angular frequency ωs and noise at this frequency

and at neighboring frequencies are attenuated as they travel through the amplification chain, from the output to the input, in the opposite direction to the one in which amplification occurs.

[0041] At this input end then develops of course the pump signal ωp' which has traveled through the chain from the output, and a wave of shifted frequency ωs+p', which is of much higher frequency. They are both not at frequencies liable to interfere with the source of the signal to be amplified (typically a qubit), because they are very far away from ωs.

[0042] [Fig. 2] As shown in figure 2, the emissions of the device under test (DUT) 10 and a pump microwave source 20 are, in a cryostat chamber at 20 mK, oriented toward a respective one of the two channels of a diplexer 30, the pump being filtered by a high-pass filter in one of the channels, and the signal of the device under test is filtered by a low-pass filter in the other channel. The two waves are oriented by the diplexer 30 via its common port then serving as output to the parametric amplifier 40 according to the invention, which is also located in the cryostat chamber at 20 mK, and the signal to be amplified exits therefrom as explained with reference to figure 1. It is directed to the common port of a diplexer 50, which is connected by respective channel ports thereof to a microwave source 60, and to an isolator 70 followed by a low-noise amplifier (LNA) 80 located in a stage of higher temperature, for example 4 K, which delivers the amplified signal to a read chain 90. The waves of the microwave source 60 are filtered by a high-pass filter before being transmitted to the output of the parametric amplifier 40. The waves exiting the parametric amplifier 40 are processed by a low-pass filter before being transferred to the isolator 70. The LNA amplifier 80 produces noise that propagates through the transmission line in the direction of the diplexer 50 but is blocked by the isolator 70. Conversely, no isolator is present on the transmission line between the DUT 10 and the parametric amplifier 40, nor between the parametric amplifier 40 and the diplexer 50. This is a considerable advantage, given the bulk and drawbacks of having such an isolator in a cryostat chamber, typically in proximity to a qubit or other DUT. The diplexer 30 optionally filters, via the low-pass filter which it interfaces between the parametric amplifier

40 and the DUT 10, the pump tone ωp' that has traveled through the chain from the output, and the wave of shifted frequency ωs+p'.

[0043] [Fig. 3] Figure 3 shows the isolation obtained in the opposite direction to the amplification, with the system according to the invention. The microwave source 60 delivers a pump tone at 10.2 GHz, and this creates an isolation band of 1 GHz width and 20 dB attenuation gain, which is remarkable.

[0044] [Fig. 4] Figure 4 shows the gain of the system in either direction, for a pump tone of 10.17 GHz frequency, as a function of the flux applied to the parametric amplifier (on the x-axis) and as a function of the frequency to be amplified or attenuated (on the y-axis). The darker the hue, the more the signal is attenuated, and the lighter the hue, the more the signal is amplified. A periodicity is observed along the x-axis, of period of one flux quantum of the loops of the parametric amplifier. Symmetries with respect to the x-coordinates 0 flux quanta, 0.5 flux quanta and 1 flux quantum are also observed. Regions of attenuation are very visible from 0 to 0.5 flux quanta and from 0.5 flux quanta to 1 flux quantum, these regions varying in frequency as a function of flux value, and having a width in frequency and flux that decreases to zero on approaching 0 and 0.5 flux quanta, at which values this attenuation is no longer observed. Thus, as soon as the flux-quantum value deviates from 0 and 0.5 flux quanta, it is possible to achieve attenuation.

[0045] [Fig. 5] Figure 5 shows the implementation of one embodiment of the invention, with an amplification pump tone of 9 GHz and an isolation pump tone of 12 GHz. For a bandwidth of 250 MHz, an isolation of 20 dB is obtained in the direction to be isolated and a gain of 20 dB is obtained in the direction to be amplified.

[0046] Regarding the construction of the SNAILs, if the number of Josephson junctions on one arm (the small junctions) is denoted n1, and the number of Josephson junctions on the other arm (the large junctions) is denoted n2, then n1 is preferably different from n2 ($n1 \neq n2$). In particular, if there is a single small junction, there must be at least two large Josephson junctions. Large junctions of 200 pH and small junctions of 1500 pH may be selected.

[0047] The ratio of critical currents of the junctions in each arm (small and large junctions) and the number of junctions in each arm are parameters that may be used to adjust the attenuation triggered by a pump of given frequency, and the amplification triggered by a pump of another frequency.

CLAIMS

1. A microwave signal amplifier comprising a chain (40) of nonlinear inductive dipolar elements each forming one superconducting asymmetric loop of Josephson junctions, said chain being arranged between an input of the chain where a signal to be amplified of known frequency (10) is applied and an output of the chain where an output signal develops, the amplifier in addition comprising a controllable system for generating magnetic flux with a view to making a current flow through said loops, the amplifier in addition comprising a first microwave pump (20) and a first coupling means (30), the first coupling means coupling said input of the chain to the first pump (20), the first pump (20) generating through the first coupling means (30) a wave in the chain (40) in the direction running from the input to the output and of frequency set to transfer power to microwaves propagating in a band around the frequency of the signal to be amplified, the amplifier in addition being **characterized in that** it further comprises a second microwave pump (60) and a second coupling means (50), the second coupling means (50) coupling said output of the chain to said second pump (60), the second pump (60) generating through the second coupling means (50) a wave in the chain (40) in the direction running from the output to the input, at a frequency different from the frequency of the first pump (20) and so as to attenuate in said direction running from the output to the input microwaves also propagating in a band around the frequency of the signal to be amplified.

2. The microwave signal amplifier as claimed in claim 1, characterized in that the dipolar elements of the chain are identical, and in that the magnetic flux is, divided by the flux quantum of the loops, set so as to be non-zero modulo 0.5, and preferably so as to be between 0.05 and 0.35, and preferably between 0.1 and 0.3.

3. The microwave signal amplifier as claimed in claim 1 or claim 2, characterized in that nonlinear asymmetric inductive elements of the chain comprise, between their two poles, a first arm and a second arm that are connected in parallel with each other, the first arm consisting of an array of at least

two Josephson junctions in series, the second arm consisting of a single Josephson junction or of a second array of Josephson junctions in series, a number of Josephson junctions in the second array being lower than a number of Josephson junctions in the first array.

4. The microwave signal amplifier as claimed in any of claims 1 to 3, characterized in that the dipolar elements and the system for generating magnetic flux are configured in such a way that the asymmetric loops of successive dipolar elements along the chain are subjected to a magnetic flux of similar magnitude but the direction of which is opposite from one asymmetric loop to a following loop in the chain, and preferably from one asymmetric loop to the immediately following loop in the chain.

5. The microwave signal amplifier as claimed in any of claims 1 to 4, characterized in that the nonlinear asymmetric inductive elements comprise, between their two poles, an arm comprising one or more identical small Josephson junctions and an arm comprising one or more identical large Josephson junctions, a ratio r of the critical current of small and large junction being between 0.01 and 0.25, and preferably between 0.05 and 0.20.

6. The microwave signal amplifier as claimed in any of claims 1 to 5, characterized in that the superconducting nonlinear asymmetric inductive elements comprise, between their two poles, an arm comprising a single so-called small Josephson junction and an arm comprising three identical so-called large Josephson junctions in series.

7. The microwave signal amplifier as claimed in any of claims 1 to 6, characterized in that the nonlinear asymmetric inductive elements comprise small and large Josephson junctions, the small Josephson junctions having an inductance between 1300 and 2500 pH and preferably between 1600 and 2200 pH, or the large Josephson junctions having an inductance between 100 and 300 pH and preferably between 140 and 260 pH.

8. The microwave signal amplifier as claimed in any of claims 1 to 7, characterized in that the system for generating magnetic flux consists of a single electromagnet developing a uniform magnetic field over the entire chain.

9. The microwave signal amplifier as claimed in any of claims 1 to 8, characterized in that the chain comprises between 500 and 1300 nonlinear inductive dipolar elements, and preferably between 600 and 850.

10. The microwave signal amplifier as claimed in any of claims 1 to 9, characterized in that the first pump emits a microwave at a frequency between 5.2 and 10.5 GHz, and preferably between 6.0 and 10 GHz.

11. The microwave signal amplifier as claimed in any of claims 1 to 10, characterized in that the second pump emits a microwave at a frequency between 8.4 and 13.5 GHz, and preferably between 9.7 and 13.5 GHz.

12. The microwave signal amplifier as claimed in any of claims 1 to 11, characterized in that a frequency difference between the microwaves emitted by the first pump and the second pump is between 2 and 6 GHz, the second pump emitting at a higher frequency than the first pump.

13. The microwave signal amplifier as claimed in any of claims 1 to 12, characterized in that the signal to be amplified is present at a frequency of the order of between 5.0 and 7.8 GHz, and preferably between 6.0 and 6.4 GHz.

14. The microwave signal amplifier as claimed in any of claims 1 to 13, characterized in that the first coupling means is a diplexer applying a high-pass filter to the microwaves of the first pump and directing them to the chain, and applying a low-pass filter to the microwaves of the signal to be amplified and also directing them to the chain.

15. The microwave signal amplifier as claimed in any of claims 1 to 14, characterized in that the second coupling means is a diplexer applying a high-pass filter to the microwaves of the second pump and directing them to the chain, and applying a low-pass filter to the microwaves issuing from the chain and directing them to a read chain.